

Quiescent Light Curve of Accreting Neutron Star MAXI J0556-332

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MAXI J0556-332 is the hottest transient accreting neutron star at the beginning of quiescence. A theoretical model with crustal heating indicates that an additional shallow heating source of $Q_{\text{shallow}} > 6$ MeV per accreted nucleon is required in the shallow outer crust with respect to the deeper star crust by considering the observed decline in accretion rate at the end of outburst. However, the physical source of this shallow heating is still unclear. In the present investigation, we perform stellar evolutionary calculations adopting the effects of outburst behavior of the accretion rate. As a consequence, we find that the quiescent light curve of MAXI J0556-332 can be well explained on the whole with the inclusion of the nuclear energy generation due to the hot CNO cycle.

1. Introduction

Observations of quiescent X-ray luminosity from accreting neutron star transients has opened a new probe to explore the physics of neutron star structure.¹⁻⁴⁾ Transiently accreting neutron star experiences periods of outburst activity separated by long phases of relative quiescence period during which accretion is switched off or strongly suppressed. The accreted crust is heated during outburst by electron captures, neutron emission, and pycnonuclear reactions that release 1-2 MeV per accreted nucleon.⁵⁻⁷⁾ The energy release due to crustal heating make the star hot enough to produce the quiescent light curve which is consistent with the observations.^{4,8,9)}

On the other hand, it has been advocated that the shallow outer crust ($\rho \lesssim 10^{10} \text{ g cm}^{-3}$) should be heated with respect to the deeper neutron star crust to explain the temperatures observed in the first months of relaxation for several sources; for example, the light curves of KS1731-260 and MXB 1659-29 required a shallow heating source of ≈ 1 MeV in Brown & Cumming's calculation.¹⁰⁾

MAXI J0556-332 is such an accreting neutron star transient; it was discovered in 2011 January with MAXI¹¹⁾ and went into quiescence in 2012 May. After the outburst period had continued more than 16 months, it returned to quiescence.¹²⁾ Observations of MAXI J0556-332 with Chandra and XMM-Newton started and had been analyzed by a variety of X-ray instruments. As a consequence, the Swift/XRT light curve indicates that there is an exponential decay timescale of ~ 3.3 days for the last ≈ 14 days of the outburst.¹²⁾ The Rossi X-ray Timing Explorer (RXTE) data of MAXI J0556-332 show similarities to the class of low mass X-ray binaries known as "Z-sources",^{12,13)} which implies that the neutron star in MAXI J0556-332 accretes at near- or super-Eddington limit.

Furthermore, it has been thought to be the hottest quiescent neutron star in this class, where crustal heating models cannot explain the observational data of light curve. In Deibel's detailed calculation,¹⁴⁾ an additional shallow heat source $Q_{\text{shallow}} \approx 6 - 16$ MeV per accreted nucleon is required by taking account of the decay of the accreting rate at the end

of the outburst. However, the physical source of this shallow heating is still unknown. Furthermore, the relation between the photospheric temperature and that at the bottom of accreted envelop if some heatings occur in the envelope. As for the crustal heating, it has been shown that the heat flow from the crust to the inner regions is important to explain the observation related to the X-ray burst due to helium shell burning.¹⁴⁾

In the present paper, we present theoretical fits to the light curve for the observational data of the transient source MAXI J0556-332 by adopting the stellar evolution code with the effect of the outburst behavior, where the accretion rate does not turn off instantaneously at the end of the outburst. We assume a similar decay time scale obtained from the Swift/XRT observations. In the accretion layer, the nuclear reaction from the hot CNO cycle¹⁵⁾ is included, because it will occur when the temperature goes up in the range $0.2 \leq T_9 \leq 0.5$ ($T_9 = T/10^9$ K). During the quiescent period, the energy deposited by the crustal heating, compressional heating, and hot CNO cycle will be released gradually.

In section II, we outline our thermal evolution model to fit the light curve of MAXI J0556-332. Our results compared with observations are presented in section III. Conclusions are given in the last section.

2. Cooling Model of the MAXI J0556-332

We perform calculations of the thermal evolution of neutron stars in hydrostatic equilibrium with use of the spherical symmetric stellar evolutionary code^{16,17)} which includes full general relativistic effects formulated by Throne.¹⁸⁾ Basic simultaneous differential equations are written as follows:

$$\frac{\partial M_{\text{tr}}}{\partial r} = 4\pi r^2 \rho, \quad (1)$$

$$\frac{\partial P}{\partial r} = -\frac{GM_{\text{tr}}\rho}{r^2} \left(1 + \frac{P}{\rho c^2}\right) \left(1 + \frac{4\pi r^3 P}{M_{\text{tr}} c^2}\right) \left(1 - \frac{2GM_{\text{tr}}}{c^2 r}\right)^{-1}, \quad (2)$$

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$$\frac{\partial(L_r e^{2\phi/c^2})}{\partial M_r} = e^{2\phi/c^2} (\varepsilon_n + \varepsilon_g - \varepsilon_\nu), \quad (3)$$

$$\frac{\partial \ln T}{\partial \ln P} = \min(\nabla_{\text{rad}}, \nabla_{\text{ad}}), \quad (4)$$

$$\frac{\partial M_{tr}}{\partial M_r} = \frac{\rho}{\rho_0} \left(1 - \frac{2GM_{tr}}{c^2 r}\right)^{1/2}, \quad (5)$$

$$\frac{\partial \phi}{\partial M_{tr}} = \frac{G(M_{tr} + 4\pi r^3 P/c^2)}{4\pi r^4 \rho} \left(1 - \frac{2GM_{tr}}{c^2 r}\right)^{-1}. \quad (6)$$

Here, M_{tr} and M_r are the gravitational mass and rest mass in the radius r . ρ and ρ_0 denote the total mass energy density and rest mass density. P and T are the pressure and local temperature. ε_n and ε_g describe energy generation rates by nuclear burning and gravitational energy release, respectively. ε_ν represents energy loss rate by neutrino emission. ∇_{rad} and ∇_{ad} are the radiative and adiabatic gradients, respectively. ϕ is the gravitational potential in unit mass.

We adopt the fraction of the rest mass $q [= M_r/M(t)]$ which is adopted when the stellar mass varies.^{16,19)} The gravitational energy release ε_g in Eq. (3) is expressed such as $\varepsilon_g = \varepsilon_g^{(\text{nh})} + \varepsilon_g^{(\text{h})}$, where each part in the right hand side is written as follows:

$$\varepsilon_g^{(\text{nh})} = -\exp\left(-\frac{\phi}{c^2}\right) \left(T \frac{\partial s}{\partial t} \bigg|_q + \mu_i \frac{\partial N_i}{\partial t} \bigg|_q \right), \quad (7)$$

$$\varepsilon_g^{(\text{h})} = \exp\left(-\frac{\phi}{c^2}\right) \frac{\dot{M}}{M} \left(T \frac{\partial s}{\partial \ln q} \bigg|_t + \mu_i \frac{\partial N_i}{\partial \ln q} \bigg|_t \right), \quad (8)$$

where μ_i and N_i are the chemical potential and number per unit mass of the i -th element. t is the Schwarzschild time coordinate. In Eq. (8), \dot{M} is the mass accretion rate. Eqs. (7) and (8) are respectively called nonhomologous and homologous terms, where the latter means a homologous compression due to the accretion.¹⁶⁾ It should be noted that compressional heating due to the accretion contributes significantly for the heating source as well as nuclear burning.

We adopt EoS by Lattimer & Swesty²⁰⁾ with the incompressibility of 220 MeV in the inner layers ($\rho \geq 10^{12.8} \text{ g cm}^{-3}$) and connect it to EoS of BPS²¹⁾ for the outer layers ($\rho < 10^{12.8} \text{ g cm}^{-3}$). Neutrino emission process is set to the slow cooling process;^{22,23)} electron-positron pair, photo, plasmon processes,²⁴⁾ and bremsstrahlung process. We note that the slow cooling process includes the conventional modified Urca process and do not include the neutrino emission by pion condensation. Although pion condensation accompanies the strong neutrino loss rates, effects of the super-fluidity may reduce the neutrino emissions. However the critical temperature for the super-fluid to occur is very uncertain. Since our aim is to present a possible heat source instead of unknown source, we neglect the strong neutrino emission for simplicity.

The energy generation include crustal heating,⁵⁾ compressional heating,¹⁶⁾ and the hot CNO cycle.¹⁵⁾ Crustal heating has the following form:

$$Q_i = 6.03 \times \dot{M}_{-10} q_i 10^{33} \text{ erg s}^{-1}, \quad (9)$$

where $\dot{M}_{-10} = \dot{M}/(10^{-10} M_\odot \text{ yr}^{-1})$ is the mass accretion rate, and q_i is the deposited heat per nucleon on the i -th reaction layer. Detailed tables of q_i can be found.⁵⁾ The energy generation rate ε_n in Eq. (3) can be obtained from $Q_i/\delta M$, where δM is the mass of the i -th reaction layer.

The accreted matter is assumed to have a uniform chemical composition with each mass fraction $(X, Y, Z) = (0.73, 0.25, 0.02)$, where X, Y , and Z represent the mass fractions of hydrogen, helium, and heavy elements, respectively. We adopt the simple formula of the nuclear energy generation rate for the hot CNO cycle¹⁵⁾ for the temperature range $0.2 \leq T_9 \leq 0.5$:

$$\varepsilon_{\text{hCNO}} = 5.86 \times 10^{15} Z' \text{ erg g}^{-1} \text{ s}^{-1}, \quad (10)$$

where Z' represents the sum of the mass fraction of CNO isotopes inside the accreted envelope, that is, $Z' = 0.02$.

3. Theoretical Results Compared with Observations

We make initial models of a neutron star accreted at around the Eddington rate $dM/dt = 2.73 \times 10^{-8} M_\odot \text{ yr}^{-1}$ with and without the crustal, compressional heatings, and the hot CNO cycle. The initial model corresponds to a steady state, where the nonhomologous part of the gravitational energy release (8) can be neglected.^{16,17)} The gravitational mass and radius of the neutron star are $M = 1.54 M_\odot$ and $R = 12.48 \text{ km}$, respectively. We assume a decay time scale τ (e -folding time) at the beginning of cooling, where the time scale is chosen to match the duration of the MAXI outburst.¹²⁾ We construct the light curve by tuning the mass of the accreted elements ΔM and τ for the accretion rate.

As a consequence, we show the theoretical light curve in Fig. 1 with $\Delta M = 1.2 \times 10^{-12} M_\odot$ and $\tau = 14$ days. Five curves are drawn which include four cases: the curve 'a' includes only the crustal heating (9) and the curve 'b' only the compressional heating (8). The case for the heating due to the hot CNO cycle (10) is indicated by 'c'. We note that the time is measured from the end of the outburst.¹²⁾ We find that our cooling curve ('a+b+c') can well reproduce the light curve as a whole. The dotted curves ('a+b' and 'b') show the light curves without the additional energy source of the hot CNO cycle. We recognize that the nuclear energy source of the hot CNO cycle can give the significant heating to go up the light curve in addition to the compressional and crustal heatings until around 300 day. Both the compressional and crustal heatings maintain the heating according to the decreasing accretion rate after 500 day. In particular, the light curve after 700 days is predicted thanks to the two heating sources as can be seen in Fig 1, where contribution from the compressional heating is larger than the crustal heating by a factor of 1.8.

We note that the two observational data with high effective temperatures which are not fitted by our light curve are attributed to the increase in the accretion rates¹²⁾ or contaminations due to the residual accretion.¹⁴⁾ If we include sudden increases in accretion rates, the temperature in the accretion layers goes up and further nuclear burning results. However, this may cause very complex thermal structure.

The fitting is not adequate for the last two observations. This is because we use the approximate nuclear energy generation rate of Eq. (10) for the hot CNO cycle. Figure 2 shows changes in the temperature distribution against the density during the quiescence, where the shadowed area indicates the temperature region for the envelope to reach the condition that the hot CNO cycle occurs significantly. We can see that the hot CNO cycle operates until 500 days before the flat shape of the quiescence appears. Therefore, we must at least take account of the effects of changes in the abundances during the

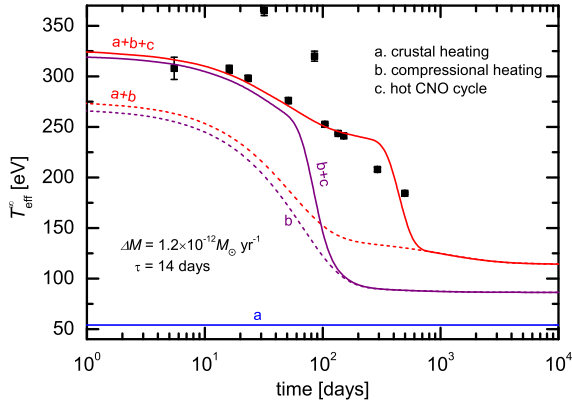


Fig. 1. Model fit to the quiescent light curve of MAXI J0556-332 for a $M = 1.54 M_{\odot}$, $R = 12.48$ km neutron star with hot CNO cycle. The two data with high effective temperatures above the theoretical light curve are considered to be contaminations from residual accretion.¹⁴⁾

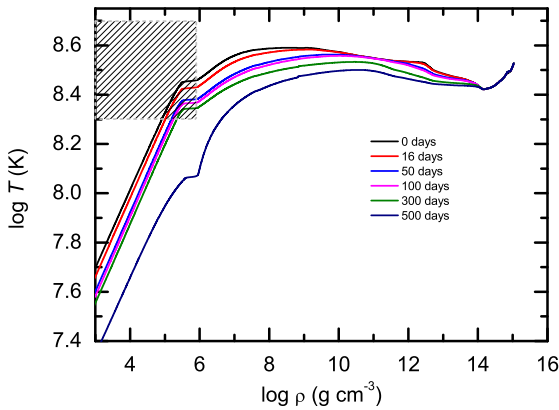


Fig. 2. Changes in the temperature during the quiescence era against the density. The shadowed rectangle indicates the region where the hot CNO cycle operates effectively. The right edge of the rectangle area indicates the bottom of the accreted envelope.

operation of the hot CNO cycle. Furthermore, our assumption for the exponential decay of the accretion rate may be inadequate to apply the last two observations of the light curve. If we should construct a reasonable initial model which reflects thermal history of the previous accretions, detailed calculations of the large nuclear reaction network could reproduce the light curve.

4. Concluding Remarks

We construct a theoretical light curve of MAXI using a stellar evolutionary code and try to fit the observations. We include nuclear burning of the hot CNO cycle in the envelope in addition to compressional and crustal heatings. Chosen the accreted mass and e -folding time, our calculations can reproduce the observed light curve as a whole. The two observations around 32 and 85 days locate significantly above our light curves. The two flare observations might be due to increases in the quiescent accretion rate¹²⁾ or contamination

due to the residual accretion.¹⁴⁾

Although we do not need to include an unknown shallow heating source compared to the previous study,¹⁴⁾ we must discuss the light curve after 200 days. As seen from Fig. 2, the hot CNO cycle which is expressed by the formula (10) does not operate enough after 300 days, because the formula can be applied for the temperature range $0.2 \leq T_9 \leq 0.5$.¹⁵⁾ Therefore, the effective temperature of our light curve decreases rather suddenly after 350 days. To explore the agreement between theoretical light curve and observations, we need to use a nuclear reaction network coupled to the stellar evolutionary calculations, which gives changes in abundances with time. This is beyond our present research, because our aim in the present investigation is to find the unknown energy source. To obtain the detailed light curve, we may further need to calculate X-ray bursts and elucidate how the bursts play a role against the quiescent luminosities.

As a matter of fact, the quiescent light curves of KS 1731-260 and MXB 1659-29¹⁰⁾ have been needed the heat source around 1 MeV per accreted nucleon as the shallow heating source. The relation between energy sources in the envelope and light curves depends on the history of the accretion and preceding X-ray bursts. These issues are worth while to study the neutron star property. It is significantly important to investigate whether light curves during quiescence eras can be reproduced with nuclear burning included. Furthermore, there remain problems such as the reheating event¹²⁾ and Urca cooling²⁵⁾ in the crust. It may be very difficult to include all these phenomena and/or nuclear processes which involve very uncertain nuclear processes.

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